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CENTRAL INTELLIGENCE AGENCY
WASHINGTON 25, D. C.

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16 AUG 1962

MEMORANDUM FOR: The Director of Central Intelligence

SUBJECT : Chapter V of SECRET Soviet Manual on Atomic Weapons and Antiatomic Protection

1. Enclosed is a verbatim translation of Chapter V of a Soviet SECRET document entitled "A Guide to the Combat Characteristics of Atomic Weapons and to the Means of Antiatomic Protection". It was published in 1957 by the Ministry of Defense, USSR.

2. For convenience of reference by USIB agencies, the codeword IRONBARK has been assigned to this series of TOP SECRET CSDB reports containing documentary Soviet material. The word IRONBARK is classified CONFIDENTIAL and is to be used only among persons authorized to read and handle this material.

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Richard Helms

Richard Helms
Deputy Director (Plans)

Enclosure

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Original: The Director of Central Intelligence

cc: The Director of Intelligence and Research,
Department of State

The Director, Defense Intelligence Agency

The Director for Intelligence,
The Joint Staff

The Assistant Chief of Staff for Intelligence,
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COUNTRY : USSR

SUBJECT : Soviet Manual on Atomic Weapons and Antiatomic Protection (Chapter V)

DATE OF INFO : 1957

APPRAISAL OF CONTENT : Documentary

SOURCE : A reliable source (B).

Following is a verbatim translation of Chapter V of a Soviet SECRET document titled "A Guide to the Combat Characteristics of Atomic Weapons and to the Means of Antiatomic Protection". This manual was published in 1957 by the USSR Ministry of Defense as a replacement for a similar 1954 manual (CSDB-35586), and is referenced in the Information Collection of the Artillery (cf. CSDB-3/649,649). It had not been superseded as of late 1961. A similar, more general document was also published by the 6th Directorate of the Ministry of Defense in 1969 (CSDB-3/649,686).

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Chapter V

The Penetrating Radiation of an Atomic Burst

Penetrating radiation is a destructive factor which is peculiar to an atomic burst. It consists of a flux of gamma rays or neutrons emitted by the burst of an atomic or thermonuclear weapon.

19. General Description and Parameters of Gamma Radiation

Gamma radiation is characterized by:

—the energy of gamma quanta, E_γ, measured as a rule in millions of electron volts; depending on the energy of the gamma quanta we can distinguish hard gamma radiation ($E_\gamma > 1$ MEV) and soft gamma radiation ($E_\gamma < 1$ MEV); this distinction is, to a certain degree, relative;

—a flux of gamma quanta N_γ, i.e., the number of gamma quanta passing through 1 cm^2 of a surface perpendicular to the axis of propagation of the gamma quanta in a unit of time (sometimes for the entire duration of the radiation);

—the radiation intensity I_γ, i.e., the quantity of energy borne by the flux of gamma quanta N ; for monochromatic gamma radiation the radiation intensity $I_\gamma = E_\gamma \times N_\gamma$ MEV/cm^2/sec.

The intensity of gamma radiation at any distance from the source of the radiation depends on:

-the activity of the source, i.e., the number of gamma quanta emitted by the source per unit of time (usually per second);

-the energy of the gamma quanta emitted;

-the distance from the source of the radiation;

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the form and dimensions of the source of the radiation;

the attenuating capacity of the medium between the source and the given point.

The destructive effects of gamma radiation are a function of its ionizing capacity, which depends not only on the flux of gamma quanta but also on their energy. The ionizing capacity of gamma radiation is defined by the magnitude of the radiation dose, D_γ. The magnitude of the gamma radiation dose is expressed in roentgens (r).

A roentgen is that dose of gamma radiation which at 0° C. temperature and standard pressure will generate 2.08×10^9 ion pairs per cm^3 of dry air.

Since 33 ev are expended in the generation of one ion pair in air, one roentgen corresponds to 6.86×10^{10} ev, or 0.11 ergs of the energy absorbed by 1 cm^3 of air.

The dose per unit of time is called the dose rate R_γ.

The ratio of the dose rate R_γ (r/sec) to the gamma quanta flux N_γ (quanta/cm^2sec) and their energy E_γ (MEV) is expressed in the following formula;

$$R_\gamma = 1.46 \times 10^{-5} \_\_ N_\gamma E_\gamma \text{ r/sec.} \quad (141)$$

In this formula, __ is the linear coefficient of absorption of gamma radiation, i.e., the energy fraction lost by a gamma quantum by ionization along a 1 cm path. Since it is customary to take air as the medium, the degree of ionization of which serves as a measure of the radiation dose or dose rate, __ in formula (141) is the absorption coefficient for air. Values of __ for air with various E_γ are given in Table 63 and in Fig. 88.

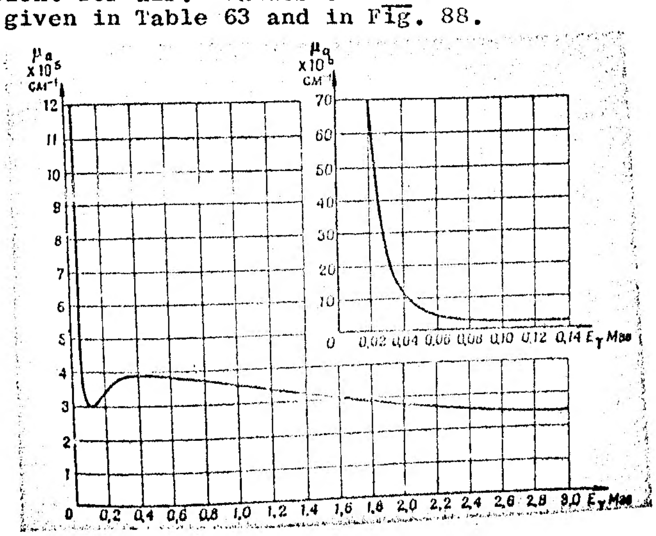

Fig. 88 Dependence of the linear coefficient of absorption μ_a for air on gamma quanta energy.

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Table 63

Values of Linear Coefficient of Absorption μ_a for Air

E_γ in MEV	μ_a in $cm^{-1} X 10^5$	E_γ in MEV	μ_a in $cm^{-1} X 10^5$	E_γ in MEV	μ_a in $cm^{-1} X 10^5$
0.02	73.4	0.4	3.9	1.8	2.9
0.04	12.0	0.6	3.8	2.0	2.8
0.06	4.5	0.8	3.7	2.5	2.7
0.08	3.3	1.0	3.6	3.0	2.5
0.10	3.1	1.2	3.5	4.5	2.1
0.12	3.0	1.4	3.2	6.0	1.8
0.20	3.4	1.6	3.1	12.0	1.4

The principal sources of gamma radiation in an atomic burst are the radioactive fission fragments present in the zone of the burst, which occupy during the first few seconds a comparatively small extent, approximately spherical in shape, and neutron capture reactions by the nuclei of nitrogen atoms of the air $N^{14} (n, \gamma) N^{15}$.

Gamma rays are emitted even during the process of the nuclear chain fission reaction. They are, however, to a great degree attenuated by the massive casing of the atomic weapon, and they do not play a real role in the overall gamma ray flux.

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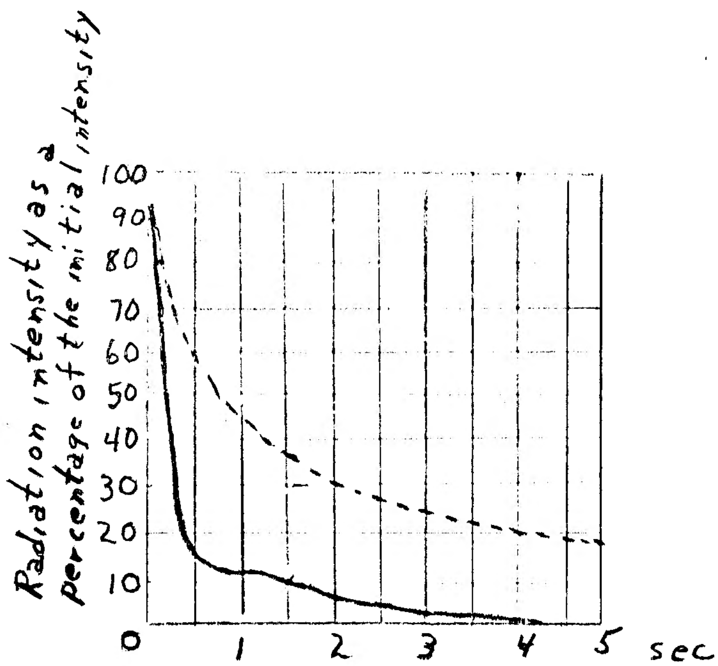

Figure 89. Change in the Intensity of Gamma Radiation with Time for Medium-Yield Weapon Burst. (The broken line shows the change in the radiation intensity of the fragments).

The intensity of gamma radiation sharply declines with time. In Figure 89 the broken line shows the decline of radiation intensity as a consequence of the rapid decrease in the overall number of radioactive fragments (mostly short-lived), occurring as a result of their decay. The solid line shows the overall drop in the intensity of gamma radiation of an atomic bomb of medium yield occurring as a result of the decay of the fragments and as a consequence of the rise of the radioactive cloud, and also as a result of the rapid (in fractions of a second) decrease in the total number of neutrons captured by nitrogen nuclei in the air.

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As is evident from the graph, approximately 5 seconds later, the intensity of gamma radiation reaching the earth's surface has decreased by a factor of hundreds. Even after ten seconds, however, the intensity of gamma radiation amounts to tens of roentgens per second. Therefore it is customary to consider that the time of action of gamma radiation on surface objects in medium-yield bursts is about 10 seconds. Where t = 0.5 to 1 sec, a sharp deceleration of the drop in radiation intensity takes place. This deceleration depends on the influence of the cavity of rarefied air (rarefied zone of the shock wave). Gamma rays pass through the rarefied air cavity almost without attenuation. The higher the yield of the burst, the greater the dimensions of the rarefied cavity and the sharper its influence on the ratio $I_\gamma = f(t)$. In high-yield explosions, a strongly pronounced maximum is even observed in the ratio $I_\gamma = f(t)$ corresponding to the time for passage through a given point of the shock wave compression zone.

Ten seconds after a burst the fission fragments of a single nucleus and the products of their decay emit on the average 3 to 4 gamma quanta. Hence it follows that in an atomic burst with a TNT equivalent of 30 kt, during which about 4×10^{24} nuclei fission, the total quantity of emitted gamma quanta amounts to

$$N_\gamma = 4 \times 10^{24} \times (3 \div 4) \approx 1.5 \times 10^{25} \text{ gamma quanta.}$$

The average energy of gamma quanta emitted by fission fragments is about 2 MEV. Therefore the energy carried off by gamma radiation is equal to $E = 2 \times 1.5 \times 10^{25} = 3 \times 10^{25}$ MEV $\approx 1.1 \times 10^{12}$ cal, i.e., it consists of about 4 percent of all the energy liberated by the burst.

The average gamma quanta energy emitted in the $N^{14}(n,\gamma)N^{15}$ reaction is equal to approximately 4 MEV, but their number is approximately equal to the gamma quanta emitted by fission fragments. However, the

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"capture" gamma radiation lasts only for tenths of a second. During this time the dimensions of the rarefied air cavity are rather small, and therefore its influence on the propagation of gamma radiation arising out of neutron capture by the nuclei of nitrogen atoms is negligible. On the other hand, the cavity exerts a substantial influence on the propagation of the gamma radiation of fragments in direct proportion to the yield of the burst. Hence it follows that the relationship between the doses caused by "capture" and radiation fragments depend on the yield of the burst: the smaller the yield of the burst the greater the proportion in the overall dose of "capture" radiation. In addition, since the energy of the gamma quanta of "capture" radiation is significantly higher than the gamma quanta emitted by fragments, the relationship between doses depends also on the distance from the center of the burst: with increasing distance the ratio of "capture" radiation grows, since it is more penetrating. At distances in excess of 1800 to 2000 m almost the entire dose of gamma radiation is short-term "capture" radiation.

The dose of gamma radiation D at various distances R from the center of an atomic burst can be calculated from the formula

$$D_\gamma = \frac{k}{R^2} e^{-R/250} \text{ r}, \qquad (142)$$

where k is a coefficient which depends on the TNT equivalent

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of the bomb; and R/250 is a multiplier which takes into account the attenuation of gamma radiation by air as a result of interaction of the gamma quanta with the atoms of the air.

The coefficient, k, is linked to the TNT equivalent, q (in kilotons), by the empirical relationship

$$k = 1.4 \times 10^{9} q [1 + 0.2 (aq)^{0.65}] \qquad (143)$$

where $a = 2$ is the coefficient for a surface burst, and $a = 1$ is the coefficient for an air burst.

Such a dependence of k on q can be explained in the first place by the change in the number of fragments proportional to the TNT equivalent, and consequently of their overall activity, and secondly by the effect of the cavity of rarefied air on the propagation of gamma rays. A graph of the relationship $k = f(q)$ is given in Figure 90.

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Table 64
Values of the Doses of Gamma Radiation at Various Distances from the Center of an Atomic Burst

Distance, in meters	Dose of gamma radiation, D_γ, in roentgens, for bursts of the following TNT equivalents. 8 kilotons		30 kilotons		150 kilotons	
	surface	air	surface	air	surface	air
200	~300000	~240000	--	--	--	--
300	83000	66000	--	--	--	--
400	31500	25000	200000	150000	--	--
500	13000	10400	83000	62000	~1000000	~700000
600	6300	5000	40000	30000	~500000	~340000
700	2900	2300	18000	13500	200000	135000
800	1600	1300	10000	7500	120000	82000
900	900	700	5500	4100	66000	45000
1000	460	370	3000	2250	36000	25000
1100	250	200	1600	1200	19000	13000
1200	140	110	900	680	10800	7400
1300	80	65	500	380	6000	4100
1400	45	35	300	220	3600	2500
1500	--	--	180	140	2200	1500
1600	--	--	100	75	1200	820
1700	--	--	60	45	700	480
1800	--	--	--	--	450	340
1900	--	--	--	--	260	180
2000	--	--	--	--	170	120
2100	--	--	--	--	100	70
2200	--	--	--	--	60	40

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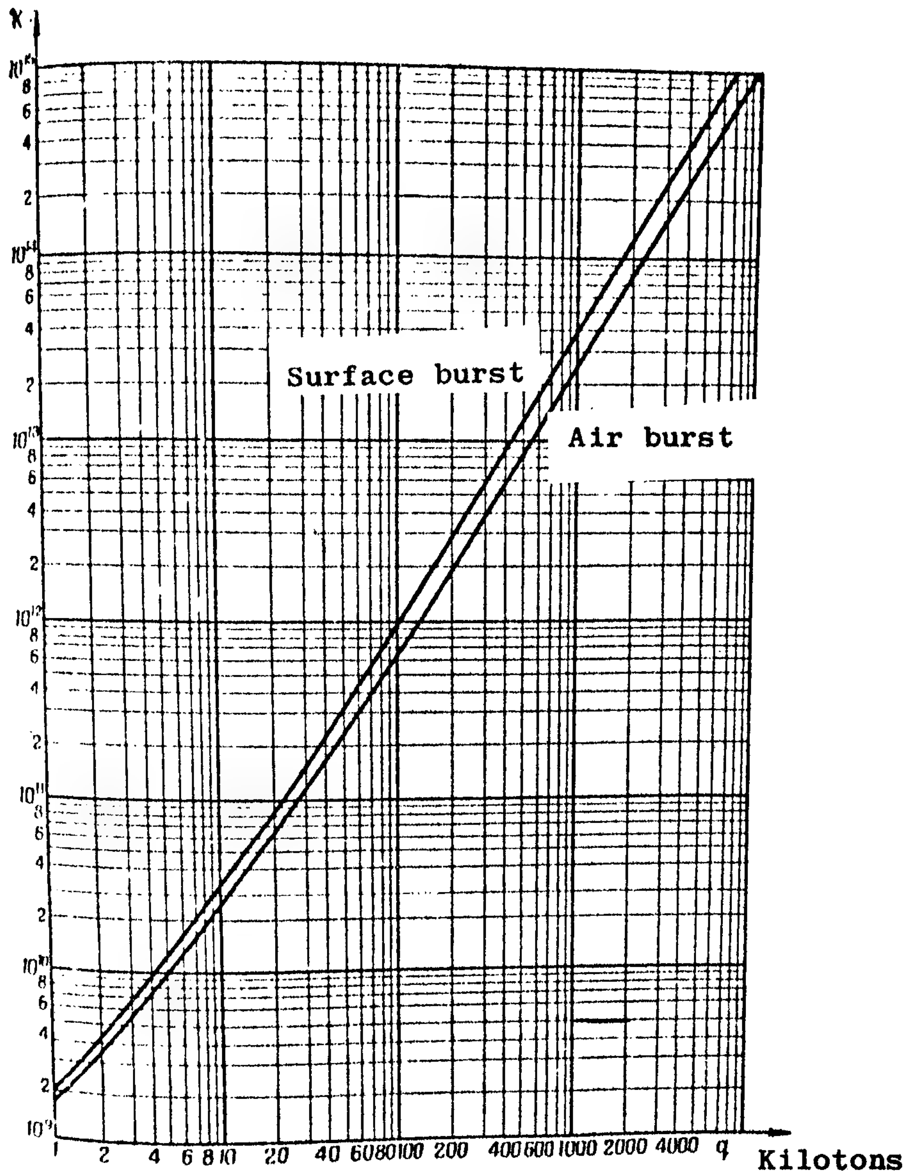

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Fig. 90. Relationship of coefficient K to TNT equivalent q.

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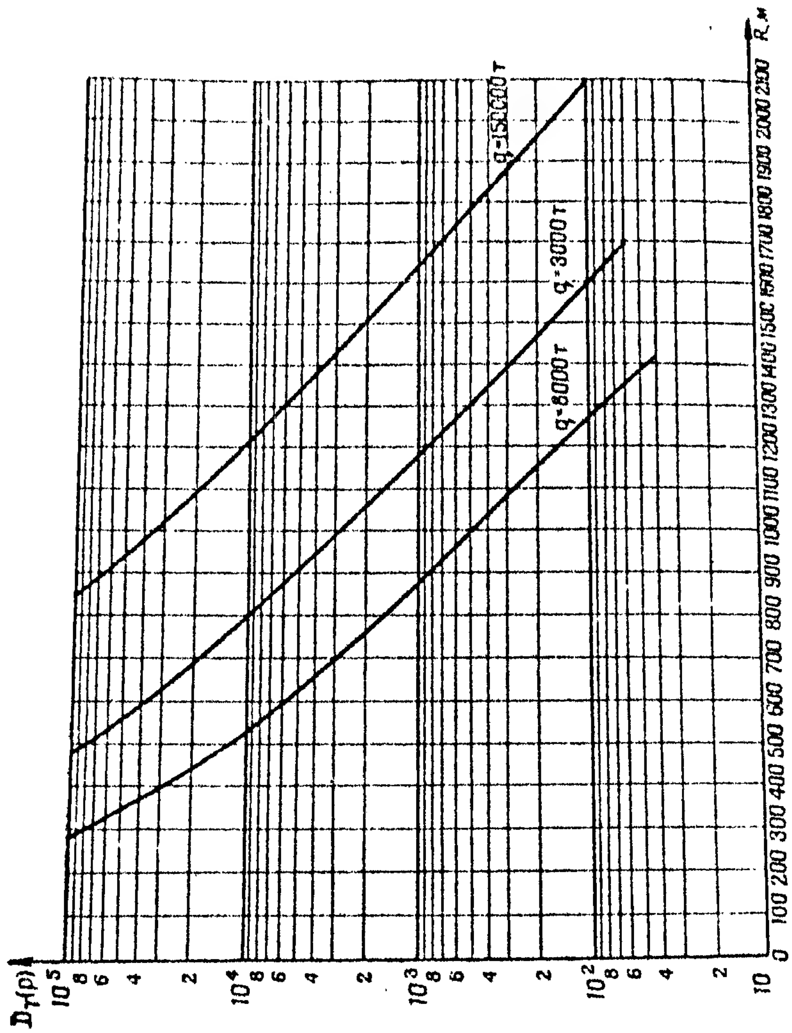

Figure 91. Dependence of Gamma Radiation Dose on Distance from Center of Burst

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Calculations, from formula (143), of the gamma radiation doses at various distances from the center of low-(q = 8 kt), medium-(q = 30 kt) and high-(q = 150kt) yield atomic bursts are given in Table 64. A graph of the relationship $D_\gamma = f(R)$ for surface bursts of the above weapons is shown in Fig. 91.

The magnitudes given in Table 64 are total doses, i.e., doses for the entire radiation time; consequently they are defined as $\int \underline{\underline{R}}_\gamma (t)dt$.

The function $R_\gamma (t)$, representing the change in dose rate with time, depends on the TNT equivalent and the distance from the center of the burst.

The greater the TNT equivalent the slower the dose rate decreases with time and the longer the action of the gamma radiation. Fig. 92 gives the approximate curves for the change in gamma radiation dose with time as a percentage of the total dose for low-, medium- and high-yield weapons.

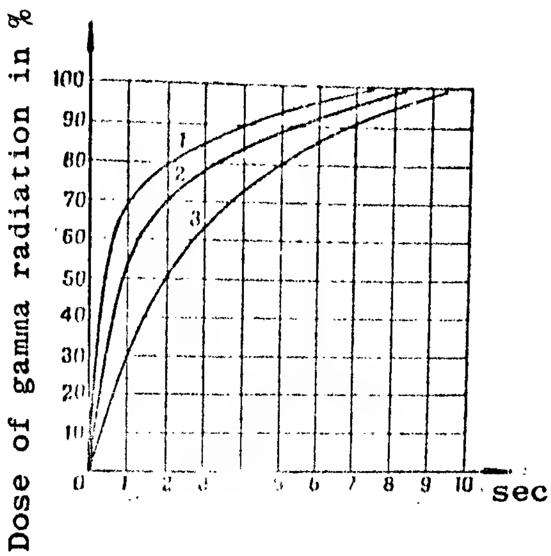

Fig. 92. Dependence of gamma radiation dose on time for weapons:

1 -- of low yield; 2 -- of medium yield;
3 -- of high yield.

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20. General Description and Parameters of a Neutron Flux

In an atomic burst neutrons are generated in the chain reaction process and during the decay of some fission products.

The number of free neutrons not involved in the chain reaction amounts to 1.5 per fission for uranium-235 and 2 per fission for plutonium-239.

Fission neutrons are emitted several microseconds after the beginning of the chain reaction and are called prompt neutrons. The emission of neutrons by fragments continues for several seconds after the burst. Such neutrons are therefore called delayed neutrons.

The greater part of the prompt neutrons, having an energy of on the average about 1 MEV, are slowed down to a very low energy level by the casing surrounding the atomic charge . The maximum energy of these neutrons, during vaporization of the casing, amounts to approximately 5 KEV. Such neutrons are not propagated over great distances. Therefore, near the center of the burst in a zone with a radius of 300 to 500 meters, there is formed a "cloud" of neutrons of great concentration.

The remaining free initial neutrons pass through the casing without appreciable loss of energy. These neutrons, just like the residual ones (having an energy of 0.4 to 0.6 MEV), are propagated at great distances from the center of the burst. Interacting with the nuclei of atoms of air, they slow down, as a result of which at a given distance from the center of a burst one can find neutrons of various energies, down to the thermal level (0.025 EV).

Although the number of residual neutrons emitted from the zone of a reaction is small in comparison to the number of initial neutrons (on the average about 0.3 per cent), in an atomic burst this correlation is greatly altered. Initial neutrons are attenuated to a considerable extent by the casing, while residual neutrons are emitted after evaporation of the casing. In addition to this the propagation of residual neutrons is facilitated by the formation of the cavity of rarefied air. As a consequence, the proportion of residual neutrons in the overall neutron flux of an atomic burst grows significantly. It has been established experimentally that they constitute about 20 per cent of a low-yield burst, about 40 percent of a medium-yield burst, and up to 90 per cent of a high-yield burst.

The spectrum of the neutrons of an atomic burst is usually divided into three groups: fast neutrons ($E_n > 1$ MEV), intermediate neutrons (100 EV $< E_n < 1$ MEV) and slow neutrons ($E_n <$ 100 EV).

For the quantitative estimate of the neutron radiation of an atomic burst, one can also make use of such features as the <u>flux</u> and <u>dose</u> of the neutrons.

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By flux is meant the overall number of neutrons of a given range of energies, which during the entire period of radiation passes through 1 cm^2 of a surface perpendicular to the direction of their movement.

The magnitude of the neutron dose is used for an estimate of the destructive effects of the neutrons on living organisms. The neutron dose is measured in biological roentgen equivalents (bre). One bre is that dose of neutrons, the impingement of which on man is equivalent to the impingement of 1 roentgen of gamma radiation.*

The destructive effects of fast and intermediate neutrons with an energy greater than 0.1 MEV are approximately the same. At one bre the total neutron flux with an energy in excess of 0.1 MEV is about 7×10^7 neutrons/cm^2.

For slow neutrons a magnitude of one bre corresponds approximately to a flux of 2×10^9 neutrons/cm^2. However, the magnitude of the dose of slow neutrons is usually ignored, since it is several times smaller than the total dose of neutrons with $E > 0.1$MEV. The magnitude of a flux of slow neutrons has the practical value that from it we can calculate the induced radioactivity of soil, types of weapons, equipment and other objects.

The total dose of neutrons with energies $E_n > 0.1$ MEV at various distances R(m) from the center of a burst is defined by the formula

$$D_n = \frac{m}{R^2} e^{-R/250} \text{ bre}, \qquad (144)$$

where m is a coefficient depending on the TNT equivalent; a graph showing m = f(q) is given in Fig. 93.

* To describe the ionizing effects of neutrons, the physical roentgen equivalent (fre) is used. One fre is that dose of neutrons the impingement of which on 1 cm^3 of material absorbs 95 ergs of energy.

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Approximate values for neutron doses at various distances from the center of burst of atomic weapons with TNT equivalents of 8, 30 and 150 kt are given in Table 65. A graph of $D_n = f(R)$, for the above weapons, is given in Fig. 94.

A flux of slow neutrons can be calculated from the rough formula

$$P_m \approx n\, e^{-R/140} \text{ neutrons/cm}^2 , \quad (145)$$

where n is a coefficient depending on the TNT equivalent; a graph of the relationship $n = f(q)$ is given in Figure 95.

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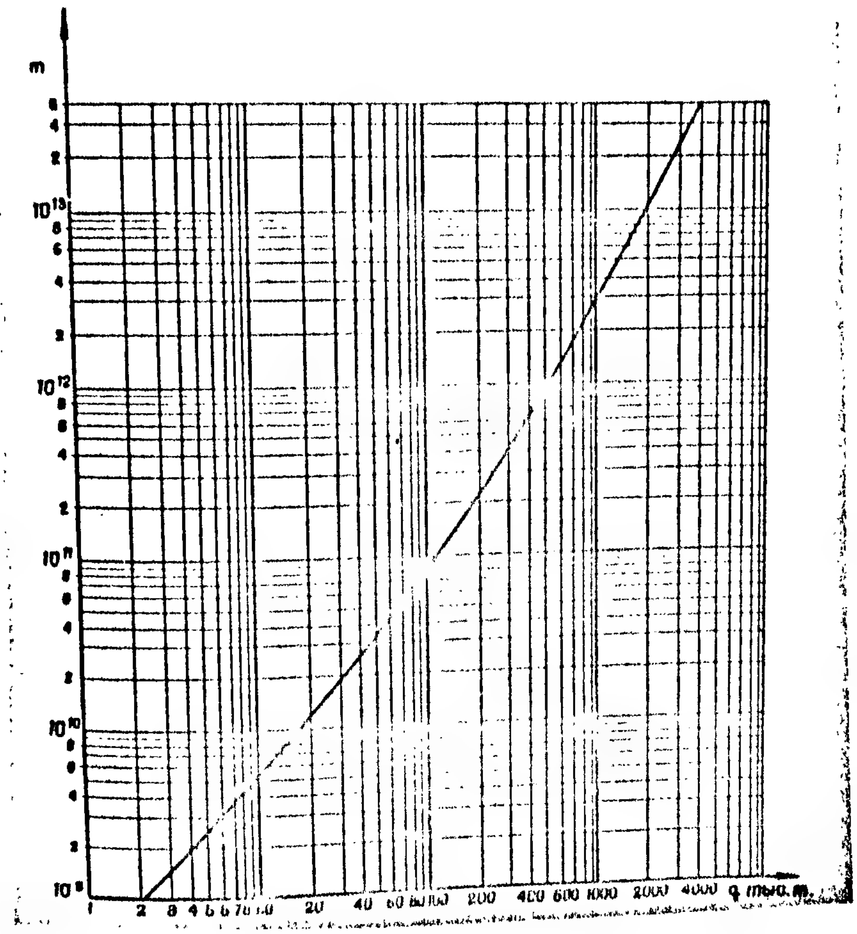

Fig. 93. Dependence of coefficient m on TNT equivalent q

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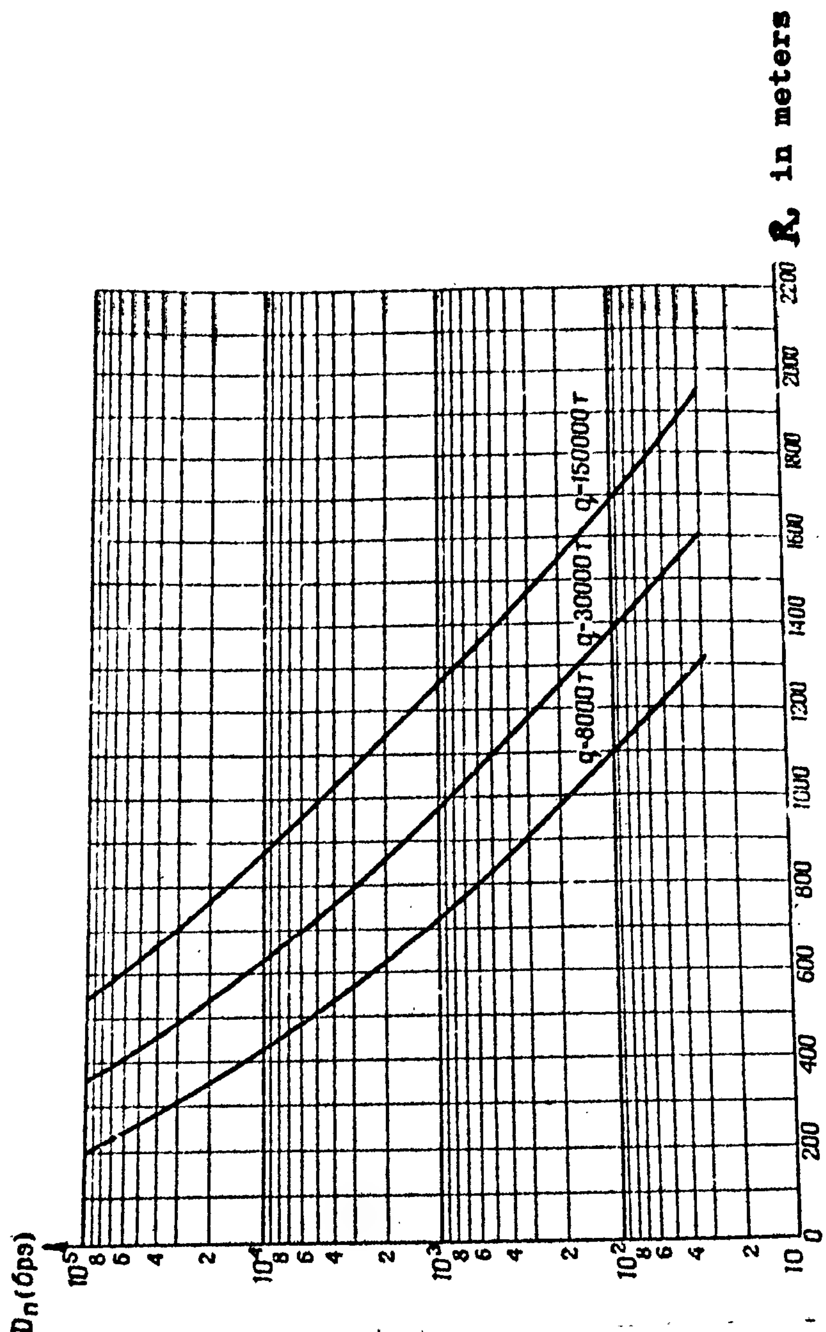

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Figure 94. Dependence of Neutron Dose on Distance from Center of Burst.

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Table 65

Values of Neutron Doses at Various Distances from the Center of an Atomic Burst

Distance, in meters	Neutron dose D_n, in bre, for bursts of the following TNT equivalents		
	8 kt	30 kt	150 kt
200	100000	--	
300	33000	165000	
400	12500	62500	
500	5200	26000	130000
600	2500	12500	62500
700	1150	5750	29000
800	630	3150	16000
900	350	1750	8750
1000	185	925	4600
1100	100	500	2500
1200	55	275	1400
1300	30	150	750
1400	--	90	450
1500	--	55	275
1600	--	30	150
1700	--	--	90
1800	--	--	56
1900	--	--	37

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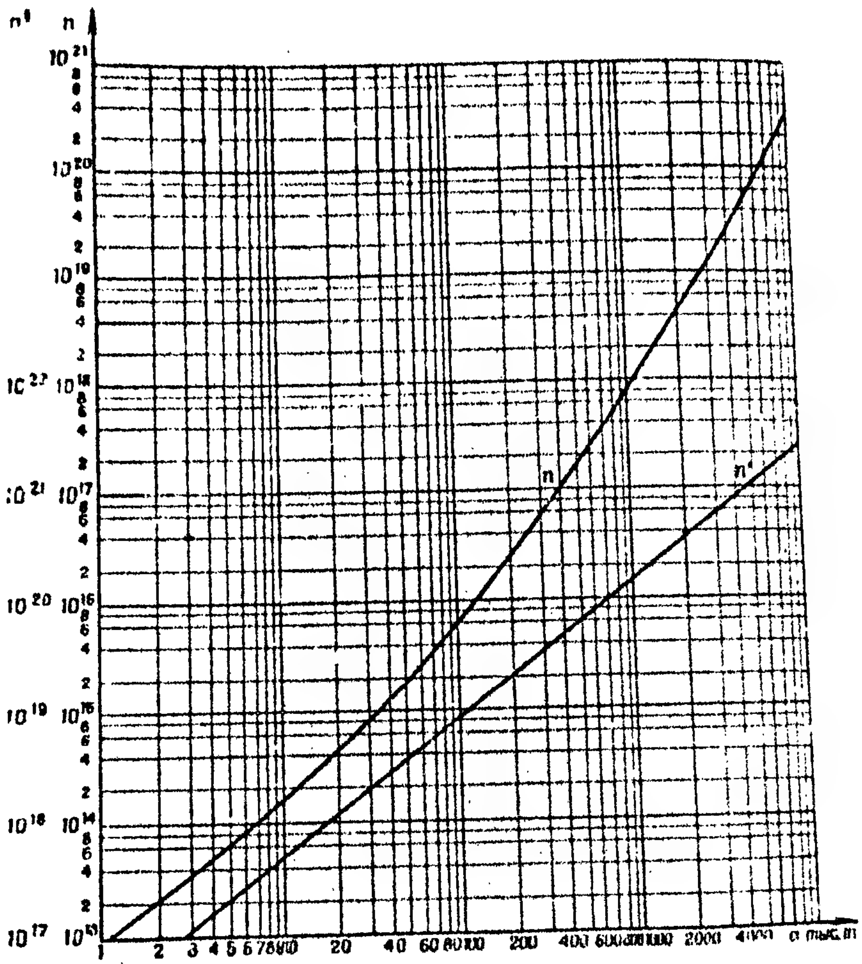

Figure 95. Dependence of the Coefficients n and n' on TNT equivalent q.

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The formula given for fluxes of slow neutrons is valid for distances in excess of 400 to 500 meters from the center of a burst. In the area up to 400 to 500 meters a flux of slow neutrons changes with distance according to the following correlation:

$$P_m \approx n' \, e^{-R/50} \text{neutrons/cm}^2. \qquad (146)$$

The values of the coefficient n' for various values of q are shown in Figure 95. The latter formula for the change of P_m in this area can be explained by the fact that in a given instance a flux of slow neutrons is made up of neutrons which have been slowed down by the casing of the bomb, and which create a "cloud" with a great concentration of slow neutrons. At great distances from the center of a burst, slow neutrons are formed by the slowing down by the air of fast and intermediate neutrons.

Approximate values for fluxes of slow neutrons, calculated by the formulas given above, are shown in Table 66.

Table 66

Values for Fluxes of Slow Neutrons at Various Distances from the Center of an Atomic Burst

Distance, in meters	Flux of slow neutrons (neutrons/cm²) of bursts of the following TNT equivalents		
	8 kt	30 kt	150 kt
100	3.3×10^{16}	2.2×10^{17}	2.2×10^{18}
200	4.6×10^{15}	3.0×10^{16}	3.0×10^{17}
300	6.2×10^{14}	4.0×10^{15}	4.0×10^{16}
400	8.4×10^{13}	5.4×10^{14}	5.4×10^{15}
500	1.1×10^{13}	7.0×10^{13}	7.0×10^{14}
600	1.8×10^{12}	1.3×10^{13}	1.5×10^{14}
700	6.7×10^{11}	5.3×10^{12}	1.0×10^{14}
800	3.4×10^{11}	2.7×10^{12}	5.1×10^{13}
900	1.7×10^{11}	1.3×10^{12}	2.5×10^{13}
1000	8.2×10^{10}	6.5×10^{11}	1.2×10^{13}
1100	4.1×10^{10}	3.3×10^{11}	6.1×10^{12}
1200	1.8×10^{10}	1.5×10^{11}	2.7×10^{12}
1300	9.1×10^{9}	7.3×10^{10}	1.4×10^{12}
1400	4.5×10^{9}	3.6×10^{10}	6.8×10^{11}
1500	2.2×10^{9}	1.7×10^{10}	3.3×10^{11}

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21. Attenuation of Penetrating Radiation by Protective Thicknesses

Attenuation of Gamma Radiation

Gamma radiation interacts with the atoms of the medium through which it passes, as a result of which the intensity of the radiation diminishes.

The main types of gamma radiation interaction with the substance of a medium are: photoelectric absorption, scattering and the formation of electron-positron pairs.

In photoelectric absorption a gamma quantum gives up its entire energy to the electron of an atom. A part of this energy (generally 30 to 50 EV) is expended on knocking the electron out of the electron shell of the atom, and the remainder is transformed into kinetic energy of the electron. Photoelectric absorption is defined by the linear coefficient, μ_{fe} cm^{-1}, which is also often expressed as τ.

With scattering as a result of a collision with electrons, gamma quanta give up to the electrons a part of their energy and change the direction of their motion, i.e., they are scattered. Scattering is expressed by the coefficient μ_{ras} (cm^{-1}), with the equation

$$\mu_{ras} = \mu_r + \mu_p$$

where μ_r is a coefficient defining the amount of energy of gamma radiation which is carried a distance of 1 cm by the scattered gamma quanta; and μ_p is a coefficient defining the amount of energy of gamma radiation which is absorbed within 1 cm during the scattering of gamma quanta, i.e., the energy transmitted to the electrons of atoms.

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Table 67

Values of the Linear Coefficient of Attenuation, μ, and of the Average Free Travel, λ, for Gamma Quanta of Various Energies

Medium	Density, in g/cm^3	Energy of Gamma Quanta, in MEV: 0.5		1.0		1.5		2.0		2.5		3.0	
		μ, in cm^{-1}	λ, in cm	μ, in cm^{-1}	λ, in cm	μ, in cm^{-1}	λ, in cm	μ, in cm^{-1}	λ, in cm	μ, in cm^{-1}	λ, in cm	μ, in cm^{-1}	λ, in cm
Air, under normal conditions (μ x 10^4)	0.00129	1.12	90x10^2	0.81	120x10^2	0.64	156x10^2	0.55	180x10^2	0.50	200x10^2	0.44	230x10^2
Water	1.00	0.096	10	0.07	14	0.057	18	0.048	21	0.042	24	0.038	26
Wood	0.7	0.065	15	0.048	21	0.038	26	0.033	30	0.029	34	0.025	40
Earth	1.6	0.14	7	0.10	10	0.081	12	0.081	15	0.061	16	0.054	19
Concrete	2.4	0.21	5	0.15	6.5	0.12	8.5	0.10	10	0.092	11	0.082	12
Aluminum	2.6	0.22	4.5	0.17	5.9	0.13	7.5	0.11	9.1	0.10	10	0.095	10.5
Iron	7.8	0.68	1.5	0.48	2.1	0.40	2.5	0.34	2.9	0.30	3.3	0.28	3.6
Lead	11.3	1.7	0.6	0.80	1.25	0.58	1.7	0.47	2.1	0.44	2.3	0.44	2.3

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The formation of pairs is also a process by which a gamma quantum is transformed into two particles -- an electron and a positron. The formation of pairs occurs only when the energy of gamma quanta exceeds 1.02 MEV. The attenuation of gamma radiation as a result of the formation of pairs is defined by the coefficient, μ_{par} (cm-1).

The complete linear coefficient of attenuation of gamma radiation, μ, equals

$$\mu = \mu_{fe} + \mu_{ras} + \mu_{par} \quad .$$

The inverse magnitude of μ is known as the average free travel of gamma quanta, λ (cm).

The values of μ and λ for several substances and for various energies of gamma quanta are shown in Table 67.

For those materials not shown in Table 67, μ is defined by the correlation

$$\mu_x = \mu \frac{\rho_x}{\rho} \qquad (147)$$

where μ is the linear coefficient of attenuation of a substance with a density ρ in g/cm^3 (determined from Table 68); and ρ_x is the density of the substance for which μ is being determined.

A more exact correlation can be obtained if, instead of density in g/cm^3, we take the electron density, i.e., the number of electrons in 1 cm^3 of a given substance. Electron density, ρ_e, can be determined from the formula

$$\rho_e = 6.02 \times 10^{23} \sum \frac{a_i \rho z_i}{A_i}, \qquad (148)$$

where a_i is the relative proportion of a given element in the substance (by weight);

z_i is the charge of the nucleus of a given element;

A_i is the atomic weight of a given element;

ρ is the density of the substance in g/cm^3.

The electron densities of several substances are given in Table 68.

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Table 68
Electron Densities of Certain Materials

Material	Density, in g/cm^3	Electron density, in $electrons/cm^3$
Air	0.00129	3.89×10^{50}
Wood	0.7	2.24×10^{23}
Water	1.0	3.34×10^{23}
Earth	1.6	4.85×10^{23}
Concrete	2.4	7.30×10^{23}
Aluminum	2.6	7.86×10^{23}
Iron	7.8	2.2×10^{24}

Attenuation of a dose of gamma radiation with a narrow monochromatic flux follows the exponential equation:

$$D = D_o e^{-\mu h}, \qquad (149)$$

where D is the gamma radiation dose after passage through a medium of h thickness, in centimeters; and D_o is the gamma radiation dose in front of the medium.

Attenuation of a broad monochromatic flux of gamma rays follows the more complex equation:

$$D = D_o e^{-\mu h} V_h, \qquad (150)$$

where V_h is a coefficient taking account of the increase of the dose with the thickness of the material h(cm) as a result of the action of radiation scattered within the thickness.

For gamma radiation with an energy of about 1.8 to 2 MEV, the magnitude of V_h is determined from the following formula:

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for media consisting of the atoms of light elements (air, wood, earth, concrete, brick, etc.),

$$\underline{V}_h = 1 + 0.44\mu h + 0.015\,\mu^2 h^2 \; ; \qquad (151)$$

for iron (armor)

$$\underline{V}_h = 1 + 0.15 \quad h + 0.002\ h^2; \qquad (152)$$

for lead

$$\underline{V}_h = 1 + 0.1h + 0.002\ h^2 \qquad (153)$$

The gamma radiation from an atomic burst is not homogeneous: it consists of gamma quanta of various energies, so that with the increase of distance an ever-growing proportion of the overall gamma radiation flux is taken up by scattered gamma radiation, which has a lower energy and consequently a lower penetrating capability. For this reason the exponential equation for the diminution of the dose is valid only beginning from a certain thickness of material, h_o. At the surface a layer of material with a thickness of h_o undergoes a sharper falloff in the dose as a result of the attenuation of the softer scattered gamma radiation.

Beginning from h_o the rule for the change in the dose of gamma radiation can be determined from the equation

$$D = aD_o e^{-\mu_{\underline{ef}} h}, \qquad (154)$$

where a is a coefficient taking account of the attenuation of the softer scattered radiation in the thickness h_o; and $\mu_{\underline{ef}}$ is the effective coefficient of attenuation.

Since the spectrum of gamma radiation changes with distance, it becomes softer with an increase of distance within defined limits, so that even the magnitude μ_{ef} is also a function of the distance from the center of a burst. The graph in Figure 96 shows the relationship $\mu_{ef} = f(R)$ for earth. Using the correlation (147), μ_{ef} can also be determined for other materials.

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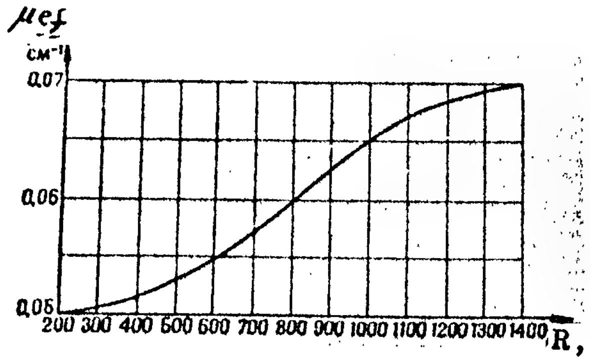

Figure 96. Dependence of μ_{ef} on Distance (for earth)

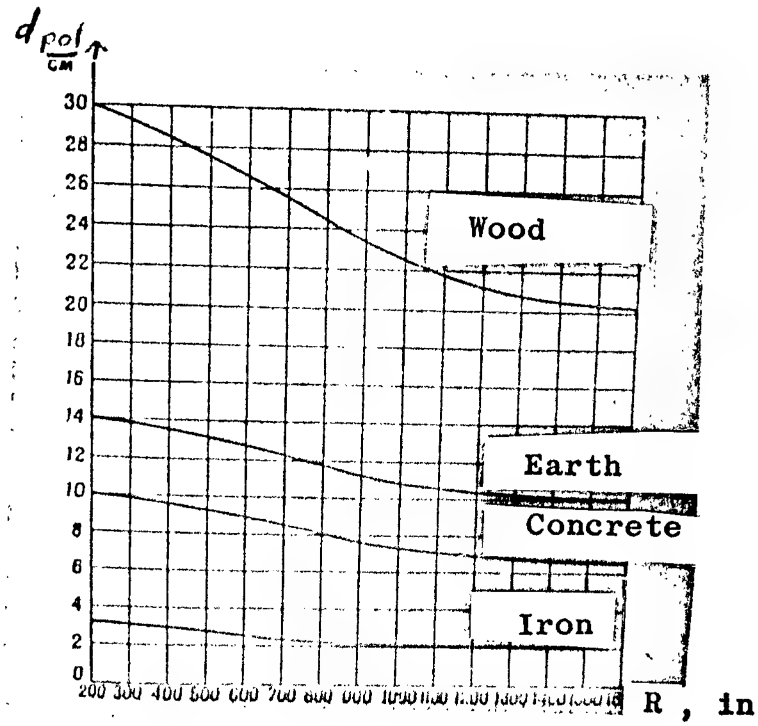

Figure 97. Dependence of d_{pol} on Distance from the Center (or ground zero) of a Burst

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Formula (154) can be represented in another way by using the half thickness, that is the layer which attenuates a dose of gamma radiation by half.

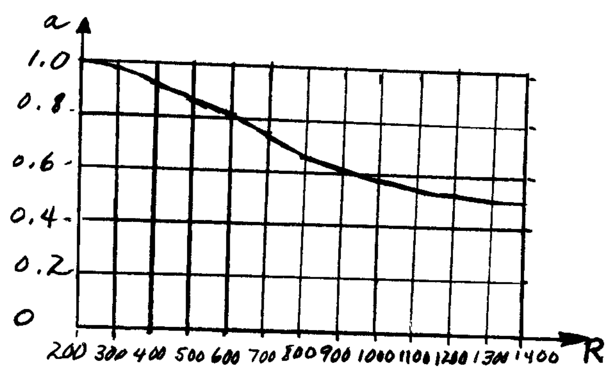
Half thickness equals

$$d_{\underline{pol}} = \frac{0.693}{\mu_{\underline{ef}}} . \qquad (155)$$

Formula (154) then takes the form

$$D = aD_o 2^{-h/d_{\underline{pol}}} . \qquad (154)$$

Graphs of the dependence of $d_{\underline{pol}}$ for earth, concrete, wood and steel and of the coefficient a, on distance from the center of a burst, R, are given in Figures 97 and 98.



, in meters

Figure 98. Dependence of Coefficient a, on Distance from Center (or Ground Zero) of a Burst

In Figures 99 and 100 graphs are given of the dependence of the coefficient of attenuation of gamma radiation

$$K = \frac{D_o}{D} \underline{=} \frac{e^{\mu_{ef} h}}{a}$$

for earth, concrete, wood and steel for minimum and maximum values of $d_{\underline{pol}}$.

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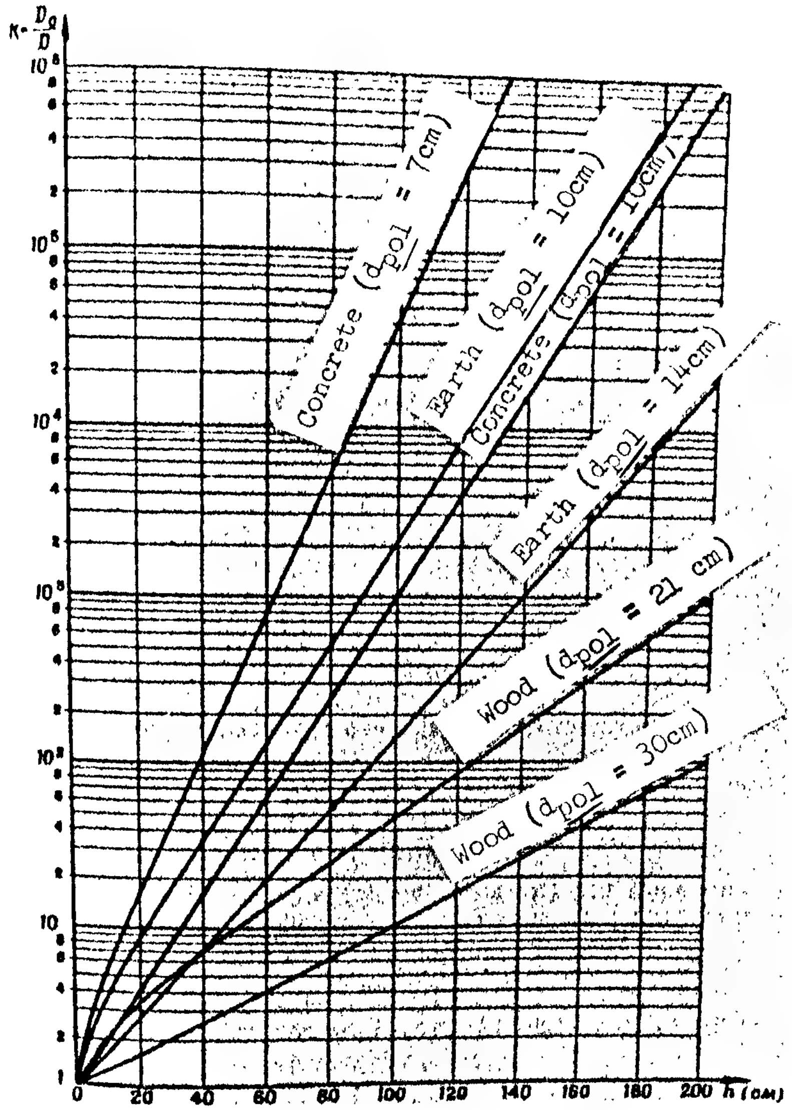

Figure 99. Attenuation of Gamma Radiation by Concrete, Earth and Wood

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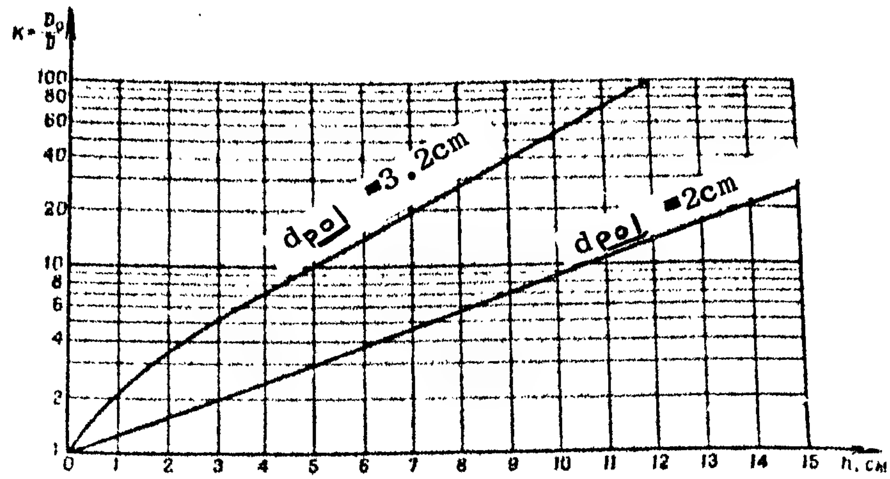

Figure 100. Attenuation of Gamma Radiation by Iron

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Attenuation of a Neutron Flux

The attenuation of a neutron flux, which occurs through neutron interaction with atomic nuclei, is defined by the cross-section of the nuclear reaction σ, expressed numerically as the probability of the interaction of a neutron with a nucleus.

There are two basic forms of interaction: scattering of neutrons and their capture by atomic nuclei.

Scattering is either elastic, like the collision of two spheres, or inelastic, in which case the neutron penetrates the nucleus. A nucleus thus excited passes in a very short interval of time to a steady state, emitting a neutron of lower energy and a gamma quantum. Scattering is the typical form of interaction for fast and intermediate neutrons. Elastic scattering can be observed with the interaction of these neutrons with any nuclei, and inelastic scattering with the heavy nuclei.

The capture of a neutron by a nucleus leads to a nuclear reaction. This form of interaction is typical for slow neutrons.

Depending on the type of interaction, we have the following cross-sections: for elastic scattering σ_{ur}; for inelastic scattering σ_{nur}; and for capture σ_{zakh}.

Cross-sections of interaction σ_{ur}, σ_{nur} and σ_{zakh}, are generally measured in cm^2 or barns (one barn = $10^{-24} cm^2$).

Just as the destructive effects of neutrons emitted by an atomic burst depend on fast and intermediate neutrons with an energy of $E_n > 0.1$ MEV, we likewise consider only the scattering processes in calculating the attenuation of a neutron flux.

Shown below are approximate methods for reckoning the attenuation of a neutron flux by various materials.

Attenuation of a Neutron Flux by Earth, Wood, Concrete, Brick and Other Materials

Elastic scattering of neutrons is typical of these materials, since they consist of atoms of the light elements. In an elastic collision a neutron transfers part of its energy to a nucleus, and changes the direction of its motion.

The change of energy of a neutron is defined by the coefficient ξ, which equals

$$\xi = \ln \frac{E_0}{E_1} \qquad (156)$$

where E_0 and E_1 correspond to the initial and final (after collision) energies of the neutron, respectively.

In agreement with the rule for the collision of elastic spheres

$$\xi = 1 + \frac{(A-1)^2}{2A} \ln\left(\frac{A-1}{A+1}\right)^* \qquad (157)$$

where A is the atomic weight (mass number) of the nucleus.

The average angle of scatter can be determined from the correlation

$$\overline{\cos\theta} = \frac{2}{3A}, \qquad (158)$$

If the material consists of several elements, then

$$\xi = \frac{\Sigma N_i \xi_i}{\Sigma N_i} \quad \text{and} \qquad (159)$$

$$\overline{\cos\theta} = \frac{\Sigma N_i \overline{\cos\theta_i}}{\Sigma N_i} \qquad (160)$$

In these formulas N_i is the number of nuclei of a given element per cm^3 of the material, and is determined thus

$$N_i = \frac{6.02 \times 10^{23} a_i \rho}{A_i} \qquad (161)$$

where A_i is the atomic weight of a given element;

ρ is the specific gravity of the medium; and

a_i is the percentage of a given element in the medium.

Considering that neutrons emitted by an atomic burst have an energy approximating 2.5 MEV or lower** and that they will have destructive effects so long as their energy does not drop below 0.1 MEV, we can find the path along which neutrons with an energy of $E_0 \approx 2.5$ MEV will be slowed down to an energy of $E_1 = 0.1$ MEV as a result of elastic collisions with the atoms of the medium. This path, which is called the retardation length L, can be approximately determined from the formula

$$L = \sqrt{\tau} \qquad (162)$$

* For elements where $A > 10$ to an accuracy of 1 percent $\xi \approx \frac{2}{A}$. For example, for iron (A=56) $\xi \approx 0.0357$.

** There are high-energy neutrons, but their number is quite small.

[redacted]

where

$$\tau = \frac{1}{3\xi(1-\overline{\cos\theta})} \int_{u_0}^{u_1} \lambda_{\underline{ras}}^2(u)\,du, \qquad (163)$$

Here $u = ln\frac{E_0}{E}$ and consequently $u_1 = ln\frac{E_0}{E_1} = ln\frac{2.5}{0.1} = 3.2.$

The function entered under the integral sign represents the square of the mean free path of a neutron from one elastic collision to another.

For a neutron of a given energy the mean free path equals

$$\lambda_{\underline{ras}} = \frac{1}{N\sigma_{\underline{ur}}} \qquad (164)$$

For a compound of elements

$$\lambda_{\underline{ras}} = \frac{1}{\Sigma N_i' \sigma_{i\,ur}} \qquad (165)$$

For approximate calculation from formula (163) we can simplify by treating λ_{ras} as a constant.

$$\tau \approx \frac{\lambda_{ras}^2 \ln\frac{E_0}{E_1}}{3\xi(1-\overline{\cos\theta})} = \frac{3.2\lambda_{ras}^2}{3\xi(1-\overline{\cos\theta})} = \frac{1.06\lambda_{ras}^2}{\xi(1-\overline{\cos\theta})},$$

$$L = \sqrt{\tau} \approx \lambda_{ras}\sqrt{\frac{1}{\xi(1-\overline{\cos\theta})}}.$$

Attenuation of a flux of fast neutrons, and consequently the diminution of their dose, can be determined from the formulas:

$$P = P_0 e^{-h/L} = P_0 2^{-h/d_{pol}}, \qquad (167)$$

$$D = D_0 e^{-h/L} = D_0 2^{-h/d_{pol}}, \qquad (168)$$

where h is the thickness of the material.

Hence the coefficient of attenuation will equal

$$k = \frac{D_0}{D} = e^{h/L} = 2^{h/d_{pol}} \qquad (169)$$

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The principal magnitudes in the formulas given above, which are required for the calculation of the attenuation of fast neutrons by various elements, are shown in Table 69.

Table 69

Basic Data on the Retardation Capacity of Various Elements

Element	Atomic Weight	ξ	$1-\overline{\cos\theta}$	Average values for σ_{vr}, in barns ranging from 0.1 to 2.5 MEV
Hydrogen	1	1.00	0.333	2.5
Carbon	12	0.158	0.944	1.0
Oxygen	16	0.120	0.958	1.3
Sodium	23	0.085	0.970	3.0
Aluminum	27	0.073	0.975	2.0
Silicon	28	0.070	0.976	1.5
Potassium	39	0.050	0.983	1.5
Calcium	40	0.049	0.983	2.0

Values for retardation lengths L and for half value layer, $d_{\rho o/}$, calculated from the above formulas for several material are given in Table 70.

Table 70

Values for Retardation Lengths L and Half Value Layer $d_{\rho o/}$ for Several Materials

Material	Density, ρ in g/cm^3	Retardation length L, in cm	Half Value Layer $d_{\rho o/}$ in cm
Water	1.0	4.5	3.1
Wood	0.7	14	9.7
Earth	1.7	17	12
Concrete	2.3	12	11.6

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Values for L and d_{pol}, calculated for materials of particular chemical composition, are shown in Table 71.

Table 71

Chemical Composition of Several Materials (principal elements)

Material	H	C	O	Na	Al	Si	K	Ca
Water	11.1	--	88.9	--	--	--	--	--
Wood	6.3	49.5	44.2	--	--	--	--	--
Earth	1.1	1.4	52.9	0.8	6.5	31.4	2.2	0.4
Concrete	1.1	--	49.2	--	2.0	26.7	--	21.0

Attenuation of a Neutron Flux by Heavy Materials

To determine the attenuation of a neutron flux by heavy materials one must take account of scatter, both elastic and inelastic. The loss of energy by a neutron is considerably greater from an inelastic than from an elastic collision. As a result of an inelastic impact a fast neutron will lose on the average about 90 percent of its energy, while with an elastic impact, e.g., with the nucleus of an atom of iron, it will lose only about 3.5 percent.

The most important practical application is to thicknesses of armor plating. Armor plate is composed of 90 to 95 per cent iron, Fe^{56}. Therefore, in calculating the attenuation of a flux of fast neutrons by armor plate, one must assume that the principal role in the attenuation of the fast neutrons is played by the process of scattering by the nuclei of iron atoms.

The retardation length for elastic scatter is determined by the same method as was described above for light materials.

[redacted]

In the range of energies from 2.5 down to 0.1 MEV, σ_{ur} is roughly constant and is equal to $3 \times 10^{-24} cm^2$ (σ_{ur} 3 barns). The number of nuclei in 1 cm^3 of iron equals

$$N = \frac{6.02 \times 10^{23} \rho}{A} = \frac{6.02 \times 10^{23} \times 7.8}{56} = 8.4 \times 10^{22} \text{ nuclei/cm}^3.$$

Hence

$$\lambda_{ras} = \frac{1}{N\sigma_{ur}} = \frac{1}{8.4 \times 10^{22} \times 3 \times 10^{-24}} \doteq 4 \text{ cm}$$

and the magnitude

$$\tau \approx \frac{1.06 \lambda^2_{ras}}{\xi(1-\overline{\cos\theta})} = \frac{1.06 \times 4^2}{0.0357(1-0.012)} = 490 cm^2.$$

The retardation length for elastic scatter is

$$L_{ur} = \sqrt{\tau} = 22 \text{ cm}.$$

The cross-section of inelastic scatter for iron equals $\sigma_{nur} = 1.16 \times 10^{-24} cm^2$. The average length of free travel between two inelastic collisions is

$$L_{nur} = \frac{1}{N\sigma_{nur}} = \frac{1}{8.4 \times 10^{22} \times 1.16 \times 10^{-24}} \approx 10 \text{ cm}.$$

The attenuation length for fast neutrons, taking account of elastic and inelastic scatter equals

$$L = \frac{L_{ur} L_{nur}}{L_{ur} + L_{nur}} = 6.9 \text{ cm},$$

and the half value layer is

$$d_{pol} = 0.693L = 4.7 \text{ cm}.$$

Thus the attenuation of a dose of neutrons by armor plate can be determined roughly by the formula

$$D = D_o e^{-h/6.9} = D_o 2^{-h/4.7}, \qquad (170)$$

where h is the thickness of the armor plate, in cm.

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By an analogous method the attenuation length for lead ($\sigma_{ur} \approx 5 \times 10^{-24}$ cm^2, $\sigma_{nur} = 1.7 \times 10^{-24}$ cm^2) equals $L \approx 12.5$ cm, and the halfvalue layer $d_{pol} \approx 8.7$ cm. The attenuation of a dose of neutrons by lead can be estimated by the formula

$$D = D_o e^{-h/12.5} = D_o 2^{-h/8.7}. \qquad (171)$$

22. Scattering of Penetrating Radiation in Air

During their propagation, gamma rays and neutrons interact with air and change the direction of their motion. The process of radiation scattering occurs repeatedly, as a result of which it acts on an irradiated object not only from the direction of the burst, but from all other directions as well.

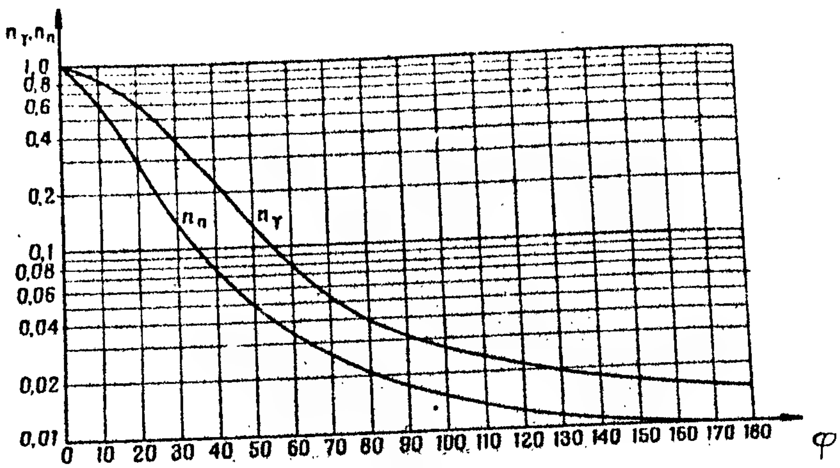

Figure 101. Dependence of n_γ and n_n on angle φ

Figure 101 shows the dependence of $n_\gamma = \frac{D_{o\gamma 2}}{D_{o\gamma}}$ and

$n_n = \frac{D_{on2}}{D_{on}}$ on angle φ, which is formed by the axis of the solid angle and the direction to the center of the burst. In these equations $D_{o\gamma}$ and D_{on} are the doses of gamma radiation and neutrons on open terrain at a given distance from the center of the burst; $D_{o\gamma 2}$ and D_{on2} are the doses of gamma radiation and neutrons produced by the action of radiation occurring at a given point from a solid angle equal to one steradian.

[redacted]

The coefficients n_γ and n_n in most cases also depend on the distance from the center of the burst, since with increase of distance the proportion of scattered radiation also increases. However, beginning at a distance of 200 to 250 meters the dependence of n_γ and n_n on R becomes insignificant and may therefore be disregarded.

The solid angle Ω for a given point is defined as $\Omega = \frac{S}{R^2}$, in steradians, where S is the area of a spherical sector limited by the lines of intersection which form a solid angle with a sphere of radius R.

A dose of scattered radiation, passing through an aperture, is characterized by solid angle Ω, estimated from the formula

$$D = D_{o\gamma\Omega} + D_{on\Omega} = D_{o\gamma} n_\gamma \Omega + D_{on} n_n \Omega . \qquad (172)$$

23. Method for Estimating the Protective Properties of Structures and Equipment

The estimation of the protective properties of structures and equipment from the effects of penetrating radiation has as its goal the determination as to whether in an atomic blast the dose of penetrating radiation inside structures or in places where equipment is located exceeds the permissible dose. Along with this one usually also takes account of the situation where a structure or equipment are located at an extremely close distance to the center (or ground zero) of a burst, which determines the resistance of the structure or equipment to the impact of the shock wave.

For a given distance calculated from Tables 64 and 65 the doses of gamma radiation and neutrons can be determined for open terrain.

Enclosed Structures. The protective thickness of a structure will attenuate a dose of gamma radiation by a factor of k_γ, and the dose inside the structure will therefore equal

$$D_\gamma = \frac{D_{o\gamma}}{k_\gamma}, \qquad (173)$$

and a neutron dose will equal

$$D_n = \frac{D_{on}}{k_n} \qquad (174)$$

The values of the coefficients of attenuation k_γ and k_n are determined by the method outlinedin Para. 21. [redacted]

The coefficient of attenuation of penetrating radiation, i.e., the total dose of gamma radiation and of neutrons, equals

$$k_{pr} \times r = \frac{D_{o\gamma} + D_{on}}{D_{\gamma} + D_{n}} . \qquad (175)$$

Since a neutron dose D_{on} is on average 30 per cent of a gamma radiation dose, the formula given may take the form

$$k_{pr} \times r \approx \frac{D_{o\gamma} + 0.3D_{o\gamma}}{\frac{D_{o\gamma}}{k_{\gamma}} + \frac{0.3D_{o\gamma}}{k_{n}}} = \frac{1.3k_{\gamma}k_{n}}{k_{n} + 0.3k_{\gamma}} . \qquad (176)$$

In the same way one can estimate the protective properties of tanks. However, one must keep in mind that for the calculations, k_{γ} and k_{n}, the protective thickness is equal not to some specific layer of armor (frontal, side, etc.) but to a certain effective magnitude, which, on the average (according to experimental data) for IS-3 tanks equals 8.5 cm, for T-54's--8.0 cm, for T-34's--5.7 cm and for PT-76's--1.0 cm.

<u>Open structures and structures with apertures</u>. For the estimation of the protective properties of such structures the total flux of penetrating radiation is divided into two parts: the first part is the gamma rays and neutrons which fall on the protective thickness and become attenuated by it while penetrating into the structure; the second is the gamma rays and neutrons which enter the structure through apertures and are therefore not attenuated. (Obviously for open structures such as trenches and connecting trenches one has to take account only of the second type of penetrating radiation.)

If the first type of penetrating radiation creates at ground level a gamma radiation dose $D_{o\gamma 1}$, and a neutron dose D_{on1}, and the second type, doses of $D_{o\gamma 2}$ and D_{on2}, then the total dose of penetrating radiation will equal

$$D_{opr} \times r = D_{o\gamma} + D_{on} = (D_{o\gamma 1} + D_{on1}) + (D_{o\gamma 2} + D_{on2}) \qquad (177)$$

The part of the radiation which enters a structure through apertures depends on the orientation of the structure relative to the center of the burst and on the magnitude of the solid

angle formed by the contour of the aperture. This part of the radiation can be determined from the graph in Figure 101, which shows the dependence of the correlation

$$n_\gamma = \frac{D_{o\gamma 2}}{D_{o\gamma}} \quad \text{and} \quad n_n = \frac{D_{on2}}{D_{on}}$$

(where the solid angle equals one steradian) on angle φ, which is formed by the axis of the solid angle and the direction to the center of the burst.

The magnitude of the dose inside a structure, depending on the radiation entering through apertures, equals

$$D_{o\gamma 2} = D_{o\gamma} n_\gamma \Omega; \qquad (178)$$

$$D_{on2} = D_{on} n_n \Omega. \qquad (179)$$

The magnitude of the dose inside a structure, which is caused by radiation passing through the protective thickness, is determined by the method outlined above for enclosed structures. However, one must subtract from the dose at ground level the magnitude of the dose entering the structure through apertures. Consequently,

$$D_{\gamma 1} = \frac{D_{o\gamma 1}}{k_\gamma} = \frac{D_{o\gamma} - D_{o\gamma 2}}{k_\gamma} = \frac{D_{o\gamma}(1 - n_\gamma \Omega)}{k_\gamma}; \qquad (180)$$

$$D_{n1} = \frac{D_{on1}}{k_n} = \frac{D_{on} - D_{on2}}{k_n} = \frac{D_{on}(1 - n_n \Omega)}{k_n}. \qquad (181)$$

The total dose of gamma radiation inside a structure will equal

$$D_\gamma = D_{\gamma 1} + D_{o\gamma 2} = \frac{D_{o\gamma}}{k_\gamma}\left[1 + n_\gamma \Omega (k_\gamma - 1)\right], \qquad (182)$$

and the total dose of neutrons

$$D_n = D_{n1} + D_{on2} = \frac{D_{on}}{k_n}\left[1 + n_n \Omega (k_n - 1)\right]. \qquad (183)$$

Consequently, the total dose of penetrating radiation inside a structure will equal

$$D_{\underline{pr}} \times \underline{r} = \frac{D_{o\gamma}}{k_\gamma}\left[1 + n_\gamma \Omega (k_\gamma - 1)\right] + \frac{D_{on}}{k_n}\left[1 + n_n \Omega (k_n - 1)\right]. \qquad (184)$$

Considering that the dose of neutrons amounts to about 30 percent of the dose of gamma rays, we find that

$$D_{\underline{pr}} \times \underline{r} = D_{o\gamma}\left\{\frac{1 + n_\gamma \Omega (k_\gamma - 1)}{k_\gamma} + \frac{0.3\ [1 \quad n_n\ (k_n - 1)]}{k_n}\right\}. \qquad (185)$$

For rough calculations for the majority of structures, except those with armor plating, the effect of neutrons can be disregarded, since their dose is relatively quite small, and the protective properties of such materials as earth, wood and concrete against gamma radiation and neutrons are approximately the same. Therefore the coefficient of attenuation of penetrating radiation for such structures can be approximately determined from the formula

$$k_{pr} \times r \approx \frac{k_\gamma}{1 + k_\gamma n_\gamma \Omega} . \qquad (186)$$

24. Penetrating Radiation from the Burst of a Thermonuclear Weapon

The typical reaction on which the blast of a thermonuclear weapon can be based is the fusion reaction of deuterium with tritium

$$_1D^2 + {}_1T^3 \longrightarrow {}_2He^4 + {}_0n^1 .$$

Neutrons formed by this reaction have an energy of about 14 MEV. Neutrons with an energy of 14 MEV are often called "super-fast". The presence of a flux of "super-fast" neutrons is a peculiarity of the penetrating radiation from the burst of a thermonuclear weapon.

Besides this type of thermonuclear reaction, it is also possible to make use of the synthesis reaction of helium from lithium and deuterium

$$_3Li^7 + {}_1D^2 \longrightarrow 2\,{}_2He^4 + {}_0n^1 .$$

The energy of neutrons emitted by this reaction is also about 14 MEV.

One of the varieties of atomic weapons is the hydrogen-uranium bomb (or other type of weapon), in which, as was already shown in para. 7, there occurs a fission reaction of the atomic nuclei of natural uranium (or more precisely, of uranium-238) by neutrons which have been formed by the thermonuclear reaction.

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Since the composition of the fission fragments of uranium-238 is approximately the same as for uranium-235 and plutonium-239, it can be assumed that the main proportion of penetrating radiation from the burst of a hydrogen-uranium bomb consists of gamma radiation from the fission fragments of uranium-238, and to a lesser degree of a flux of fast neutrons from the fission. In the overall flux of penetrating radiation, the role of super-fast neutrons for a given type of bomb is usually insignificant. Therefore the gamma radiation and neutron dose of a burst of a hydrogen-uranium bomb can be determined from the formulas given for an atomic bomb in paras. 19 and 20. As an example, Table 72 gives the data (calculated from the following formulas) for gamma radiation and neutron doses for the burst of a hydrogen-uranium bomb where the TNT equivalent, q, equals 1000 kt:

$$D_{\gamma} = \frac{4 \times 10^{12}}{R^2} \, e^{-R/250} \text{ r}; \tag{187}$$

$$D_{n} = \frac{3 \times 10^{12}}{R^2} \, e^{-R/250} \text{ bre}; \tag{188}$$

$$D_{SBN} \approx \frac{4 \times 10^{11}}{R^2} \, e^{-R/150} \text{ bre}. \tag{189}$$

Approximate Values for Gamma Radiation and Neutron Doses for the Burst of a Bomb, Where q = 1000 kt

Table 72

Distance, in meters	Gamma radiation dose, in roentgens	Fast neutron dose, in bre	Super-fast neutron dose, in bre
1000	~650,000	60,000	500
1250	170,000	12,000	70
1500	45,000	1,000	7
1750	12,000	300	--
2000	3,300	90	--
2250	1,000	20	--
2500	250	6	--
2700	65	2	--

The attenuation by various materials of the gamma radiation and of the fast neutrons of the burst of a hydrogen bomb is determined by the method described in paras. 21 and 23. 50X1-HUM